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Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

Modeling of burr size in drilling of aluminum silicon carbide composites using response surface methodology

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ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
22 February 2016
Accepted 23 February 2016
Available online

Keywords:
Drilling process
Metal matrix composite
Burr height
Burr thickness
Response surface methodology

ABSTRACT

Exit burrs produced during various machining processes degrade the product quality and functionality of different parts of assembly. It is essential to select the optimum tool geometry and process parameters for minimizing the burr formation during machining. In this paper, the effects of cutting speed, feed rate, point angle of drill bits and concentration of the reinforcements on the burrs produced were investigated. Response surface methodology has been adopted to create the quadratic model for the height and thickness of the burrs produced during drilling of Al—SiC composites. Analysis of means and variance were used to find the significance of the process parameters on the responses and to find the optimum combination of parameters to minimize the burr formation. Feed rate, point angle and concentration of reinforcements in the matrix are found to be the significant factors. Both the responses were found to be minimum for lower feed rate, higher point angle and higher concentration of reinforcements. Scanning electron microscopy was used to understand the mechanism of burr formation.

1. Introduction

Drilling is the most basic conventional machining operation that is used for creating cavities or holes for the assembly of different parts. At production stage, during drilling operations, an uncut portion of material comes out along circumference of hole. This deposition of material at entry and exit of hole is called burr. The formation of burrs creates several problems like degradation in quality and performance of precision parts etc. It is estimated that approximately 20–30% of the manufacturing cost of the finished products is required for deburring process [1]. When exit burrs are formed inside a cavity, specialized tools are required for deburring them. Hence it is essential to minimize the burr formation during drilling process. This will reduce the extra time and cost required for deburring and will ensure the quality of precision parts.

In recent times, metal matrix composites (MMCs), especially particle reinforced aluminum matrix composites, have received considerable attention in automobile and aerospace industries. Conventional materials are replaced by metal matrix composites because of high strength to weight ratio, high-specific modulus, very high resonance frequency and other excellent mechanical properties. However the presence of abrasive particles as reinforcements in metal matrix composites makes drilling extremely difficult and requires special tooling. The formation of burrs at the entry and exit of hole is a common problem when drilling these composites. The presence of brittle reinforcements and ductile matrix makes the understanding of the mechanism of burr formation extremely interesting.

Researchers have tried to understand the mechanism of burr formation in metal matrix composites. Effects of various machining parameters such as cutting speed, feed rate [1–17], and cutting environment [8] on the burr formation during drilling are studied in detail. Also the effects of drill size and geometry such as drill type [9–13], drill diameters [2,3], point angle [1,2,4–7], step angle [8,9] and lip clearance angle [1,6] on the burr sizes are also studied. The type of burrs produced during drilling of metal matrix composites is also found to be dependent on the type of reinforcements [5], volume fraction of reinforcements [5,12–15] and presence of any solid lubricants such as graphite [10,16]. In case of metal matrix composites with the brittle reinforcements, irregular and crown shape burrs are formed [7]. The cracks are developed at the site of reinforcements and solid lubricants during debonding and propagate along feed direction. These cracks restrict or slow down the flow of material due to plastic deformation toward feed direction. Hence lower burr height and thickness are reported for higher fiber concentration in metal matrix composites [10,16]. Higher feed rate increases the thrust forces and pushes the material out of the work piece rather than cutting it [16]. At a larger point angle, drill bit exerts tensile stresses on the work piece hence smaller burrs are formed

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.02.007

as the work piece material is more prone to cut than simply flow out of the surface [3,6,7]. Presence of solid lubricants in metal matrix composites sharply reduces thrust forces and results in smaller burrs [10,16].

The mathematical models have been suggested for the dimensions of the burrs produced during drilling process. A mathematical tool such as response surface methodology is a really efficient and useful tool for studying the effect of various parameters on the responses when compared to studying the effect of one variable at a time. Hence researchers preferred response surface methodology [3,7,18] for developing the mathematical model for the burr dimensions. Also other soft computing tools such as Taguchi technique [1,4,5,7,8,10,11,17], genetic algorithm [6] etc. are used for the optimization of height and thickness of burrs produced during drilling. For the optimization of multiple responses for machining processes Taguchi method can be coupled with Utility Concept [19], Grey Fuzzy Logic [20] and Principal Component analysis [21].

The formation of burrs while drilling of metal matrix composites is a serious issue and bottleneck in manufacturing process, which increases cost of manufacturing. In the current work effects of cutting parameters such cutting speed and feed rate on the height and thickness of the burrs produced during drilling of Al—SiC composites are studied in detail. Also the point angle of the drill bit and concentration of reinforcements are also selected as parameters to study the effect of tool geometry and work piece composition on the responses. Response surface methodology is employed to create a quadratic model for the burr dimensions. Analysis of variance (ANOVA) is employed to find the most significant parameters affecting the burr formation. The optimal combination of process parameters is identified to minimize the responses. The mechanism of burr formation in Al—SiC composites is studied using Scanning electron microscopy.

2. Material and method of analysis

2.1. Selection of materials

The matrix material used for these composites was aluminum 6061 alloy. Al6061 and Al6061-SiC plates of dimension $60 \times 60 \times 10$ mm^3 were used for drilling experiments. Its chemical composition is shown in Table 1. This metal matrix composites are widely used in aerospace applications and microelectronics such as high performance electronic packaging and as a substrate for power semiconductors. Average size of silicon carbide particles used as reinforcements was 2–3 µm. The weight percentages of the reinforcements selected for the fabrication of the composites were 15% and 30%.

2.2. Methods of analysis

Response surface methodology is a powerful statistical tool for mathematical modeling of engineering systems and for optimization of the process parameters. The steps of this process start with the identification of the control parameters and their domain under consideration. The next step is to select the orthogonal design and to conduct the experiments based on this design. Then the empirical models are developed between the response and the process variables. The effects of various variables and their interactions on the response are studied. The accuracy and adequacy of the developed model is checked using statistical tools such as analysis of means and analysis of variances.

Table 1
Chemical composition of Al6061 alloy.

Mg	Si	Cu	Fe	Ti	V	Mn	Zn	Cr	Zr	Ni
0.766	0.354	0.214	0.132	0.019	0.011	0.029	0.085	0.166	0.024	0.012

Table 2
Machining factors and their levels.

Factors	Code	Levels		
		−1	0	1
Cutting speed (m/min)	A	40	60	80
Feed rate (mm/rev)	B	0.1	0.15	0.2
Concentration of reinforcements (%)	C	0	15	30
Point angle (degrees)	D	96	118	140

2.3. Experimental details

Drilling operations were performed on a computer numerical control vertical machining center 'Jyoti, VMC850' with Siemen Sinumerik 828D controller. Solid carbide drills (manufactured by SANDVIK) having 10 mm in diameter and three different point angles 96°, 118° and 140° were used. In the present study, four parameters were selected for the modeling of burr height and thickness. Table 2 indicates factors and their levels selected for the study. Box–Behnken design with L_{27} orthogonal array is used for the experimentation. The experiments were conducted in random fashion. Table 3 indicates the experimental design, height and thickness of burrs produced during drilling of these. Fig. 1 indicates the schematic diagram of irregular burrs, burr height (B_h) and burr thickness (B_t). After drilling the work piece, burr height for each drilled hole was measured by Coordinate Measuring Machine 'Mitutoyo Crystal-Apex C' at four positions spaced at 90° around the circumference of hole. The thickness of burrs produced was measured at four positions using Digital Microscope 'ISM-PM 200SB'. Then average values of the height and thickness of burrs were used for the modeling using response surface methodology.

3. Results and discussion

Response surface methodology is employed to develop the mathematical model for height and thickness of burrs produced in terms of cutting speed, feed rate, point angle and concentration of reinforcements. The second order non-linear model with linear, quadratic and interactive terms is indicated by Equation (1).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_1^2 + \beta_6 x_2^2 + \beta_7 x_3^2 + \beta_8 x_4^2 + \beta_9 x_1 x_2 + \beta_{10} x_1 x_3 + \beta_{11} x_1 x_4 + \beta_{12} x_2 x_3 + \beta_{13} x_2 x_4 + \beta_{14} x_3 x_3 \quad (1)$$

The values of regression coefficients (β_0, β_1, ——, β_{14}) were determined using Minitab software (Minitab, Inc., MINITAB release 16, 2012). The analysis was done using coded units. Tables 4 and 5 indicate the results of ANOVA for both the responses. The goodness of fit of the regression model was determined by calculating R^2 coefficient, which provides a measure of how much variability in the observed response can be explained by the model. R^2 value of 91% signified that 91% of the variation in the observed values of burr height could be explained by the model while only 9% of the total variations in the response values could not be explained by the model. Higher R^2 values (approximately 91% and 89% for the burr height and thickness) indicate that the model is accurate. Also the significance of regression model can be evaluated by F and P values. The F value predicts the quality of the entire model considering all design factors at a time. The P value is the probability of the factors having very little or insignificant effect on the response. Larger F value signifies better fit of the regression model with the experimental data. The calculated values of F-ratio for models of burr height and thickness are found to be 7.84 and 6.93, higher than the standard tabulated values of F-ratio. Higher F value with low P value (below 0.05) indicates high significance of the regression model. The

Please cite this article in press as: Avinash A. Thakre, Shashank Soni, Modeling of burr size in drilling of aluminum silicon carbide composites using response surface methodology, Engineering Science and Technology, an International Journal (2016), doi: 10.1016/j.jestch.2016.02.007